Stationary - Fuel Cells

Presented to:

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16 April 2002

Tubular SOFC Hybrids:

Present and Prospect

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April, 2002

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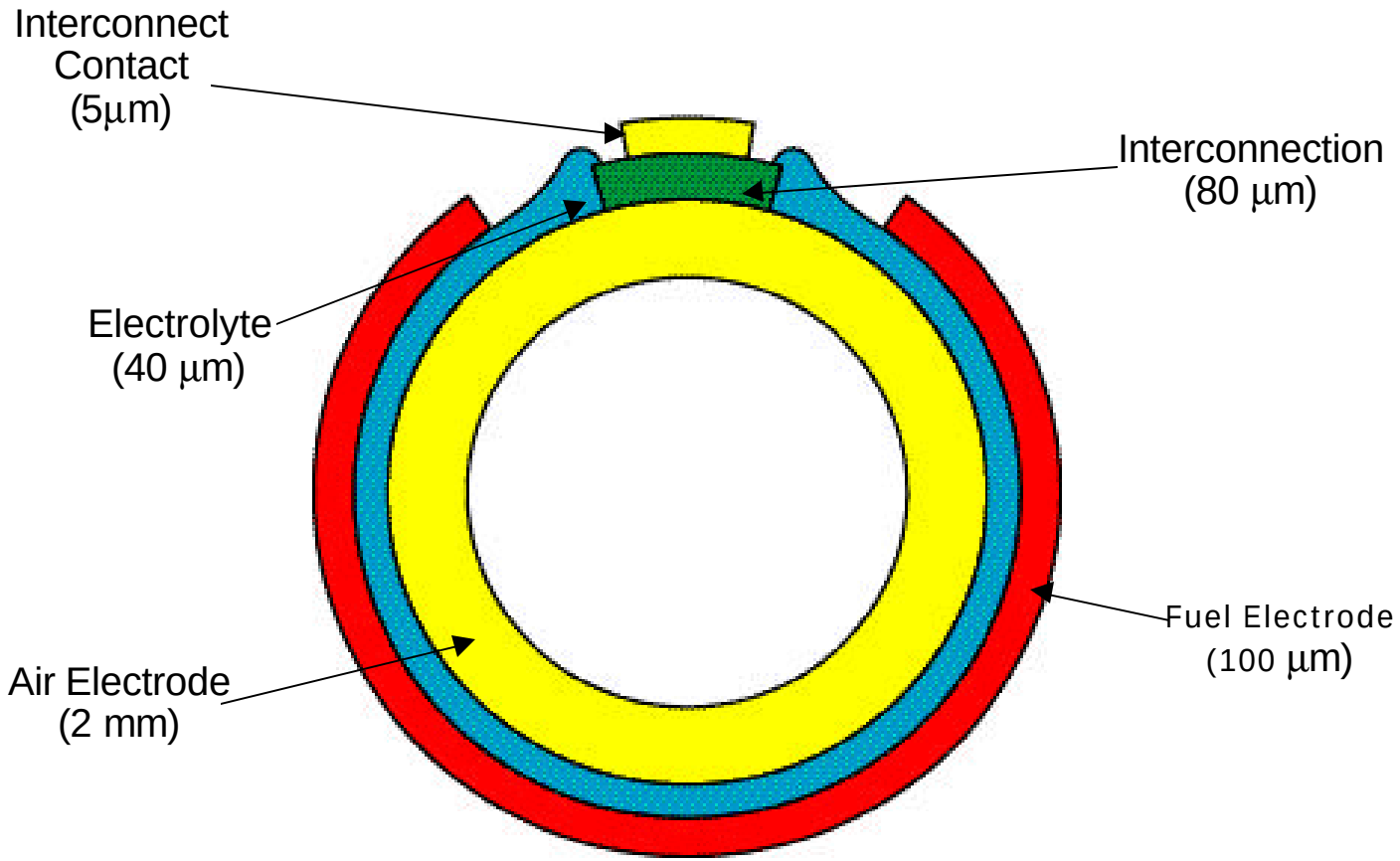
Air Electrode Supported Tubular SOFC

- **Dimensions**
  - ➢ **D = 22 mm**
  - ➢ **L = 1500 mm**
  - ➢ **A = 834 cmsq**
  - ➢ **m = 1 kg**
- **Watts @ 1 atm**
  - ➢ **In Stack = 110**
  - ➢ **Peak = 210**
- **Endurance**
  - ➢ **44,000 hrs**
  - ➢ **j=307**
  - ➢ **FU=85%**
  - ➢ **T=1000ºC**
  - ➢ **degradation**
  - ➢ **<0.1%/k-hrs**



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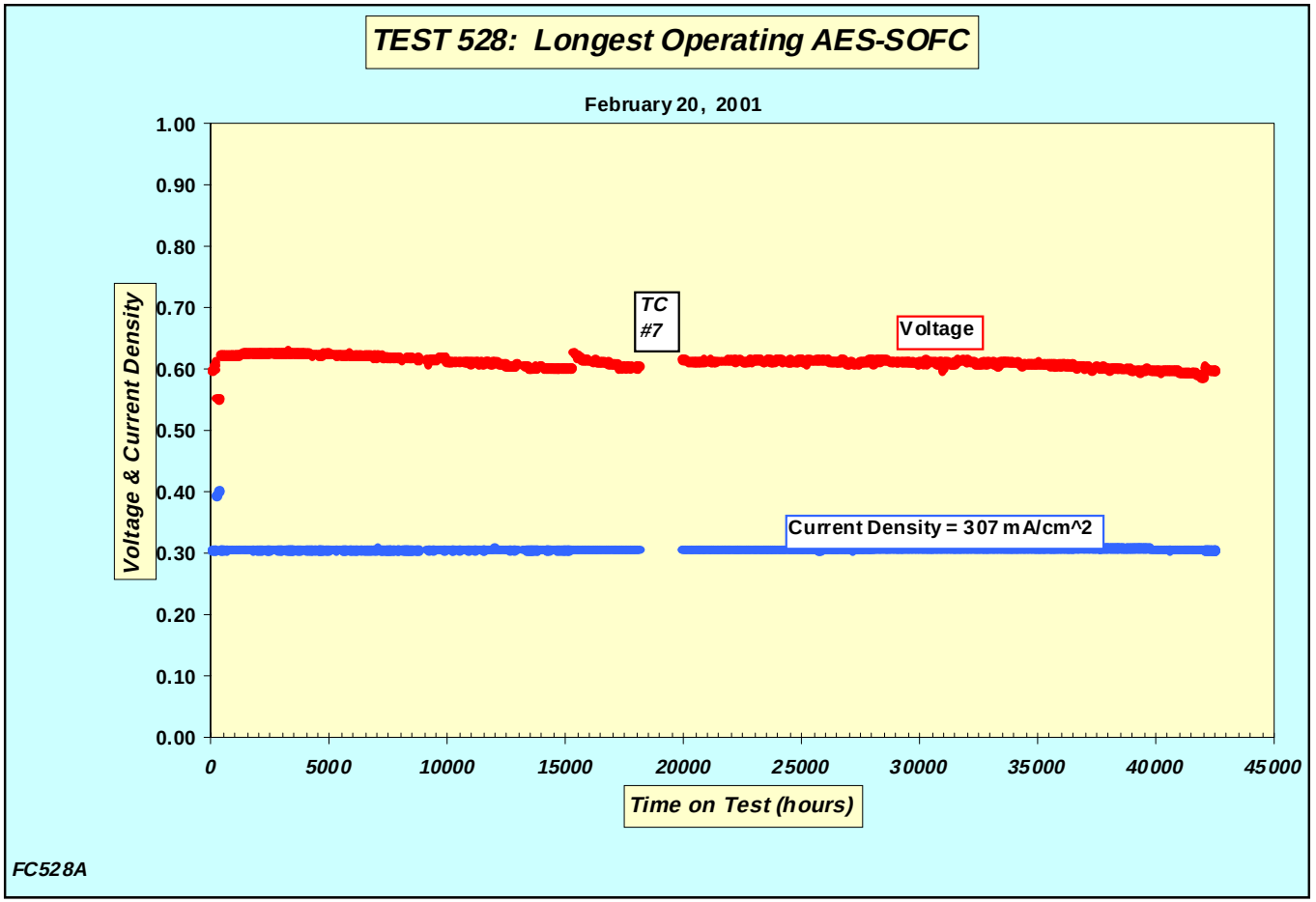
AES-SOFC Performance [T = 1000°C, FU = 0.85]



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Tubular SOFC Bundle (24 cells)

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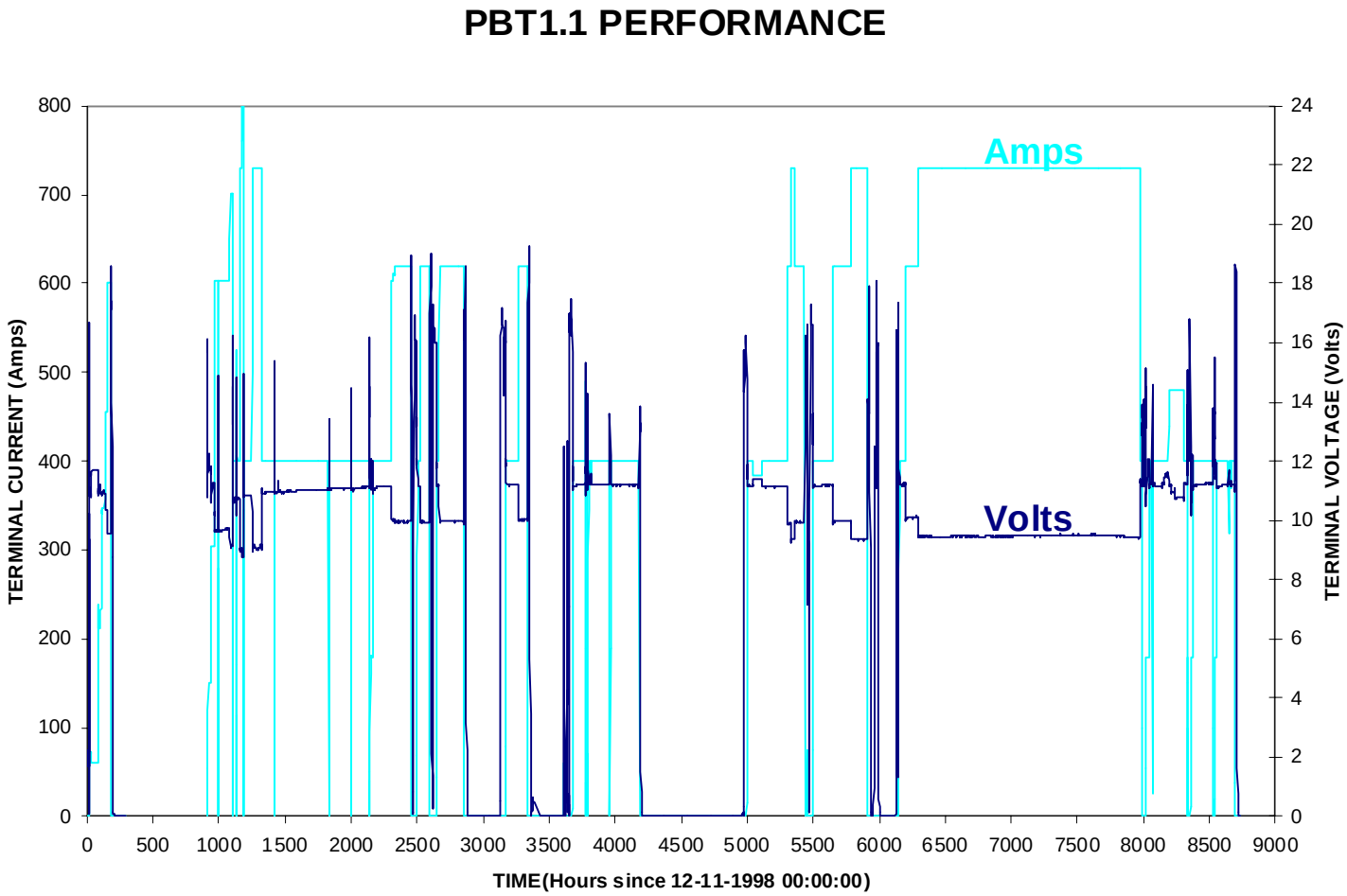
Pressurized Bundle Test

- Two Bundles
- Natural Gas
- In-stack reforming
- Ejector
- 3 atm mostly
- to 7 atm max
- 6000 hours at power
- 8 Thermal cycles



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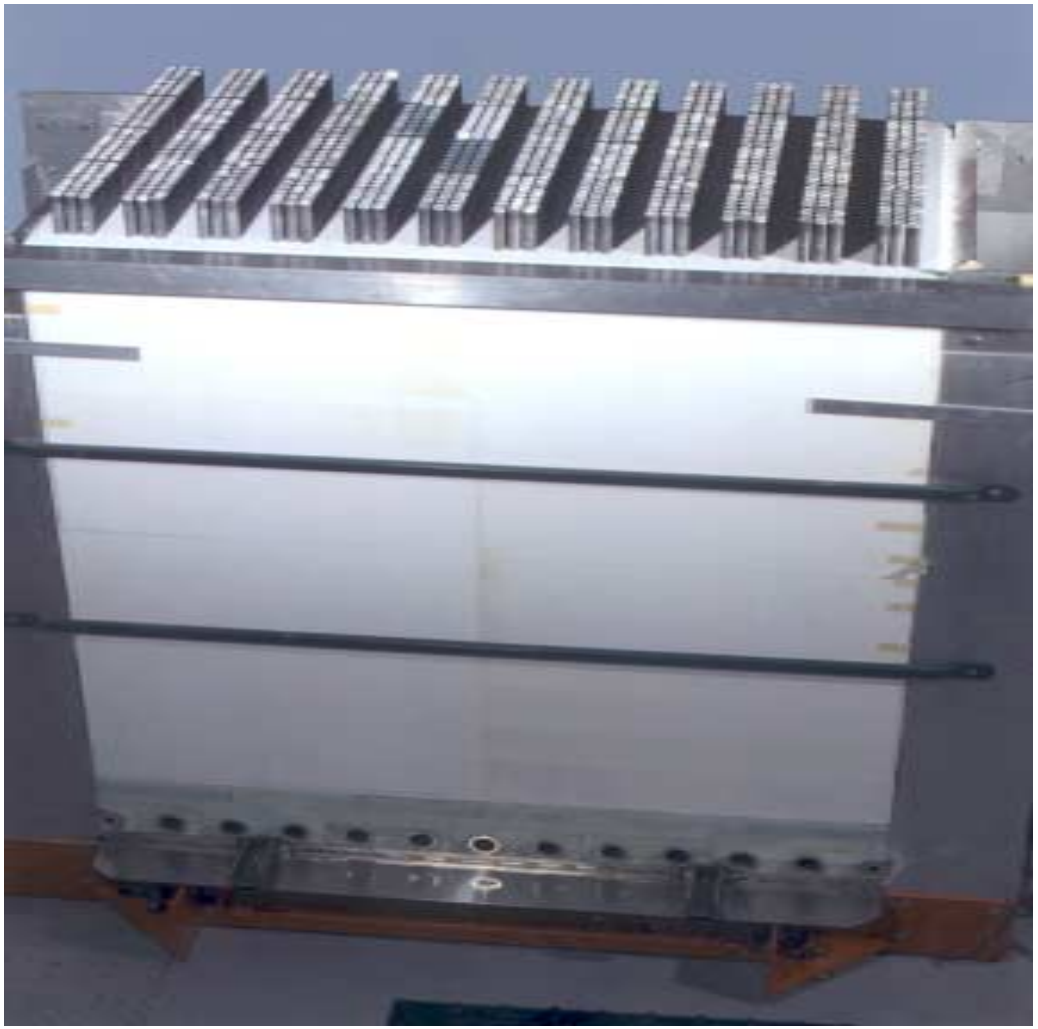
100 kWe SOFC Stack (48 bundles, 1152 cells)

- **POWER**
  - ➢ 130 kWe dc @ 1 atma
  - ➢ 180 kWe dc @ 3.8 atma



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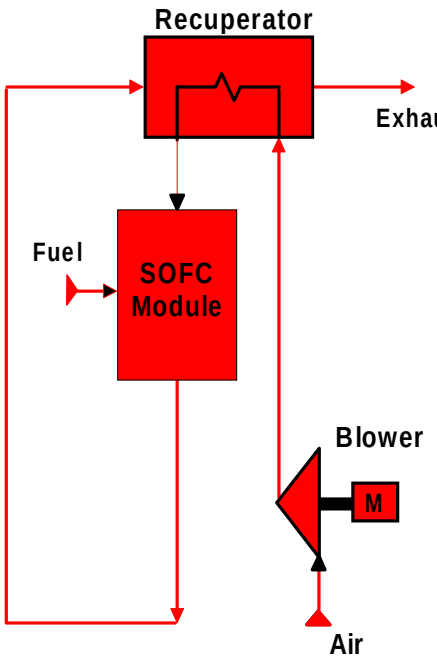
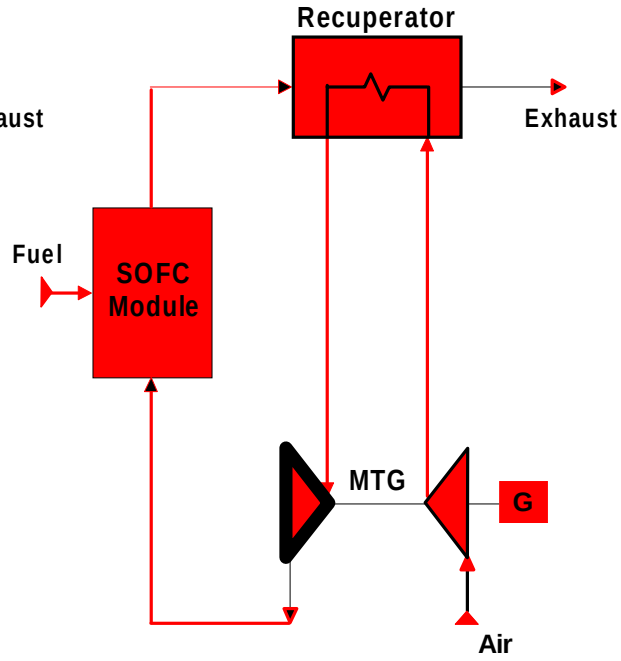
Simple Cycle Types



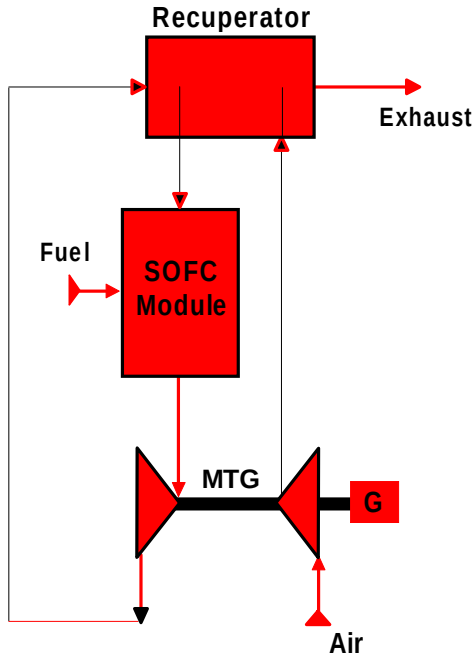
Atmospheric Pressure

$\eta \rightarrow$ 50%



Atmospheric-Pressure Hybrid

$\eta \rightarrow$ 55%



Pressurized Hybrid

$\eta \rightarrow$ 60%

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CHP100 at RWE Installation

- Natural gas
- Grid connected
  110 kWe net
- Efficiency
  46% net ac
- District Heating
- Netherlands
  16,610 hrs
- Germany
  3,870 hrs
- Degradation
  none

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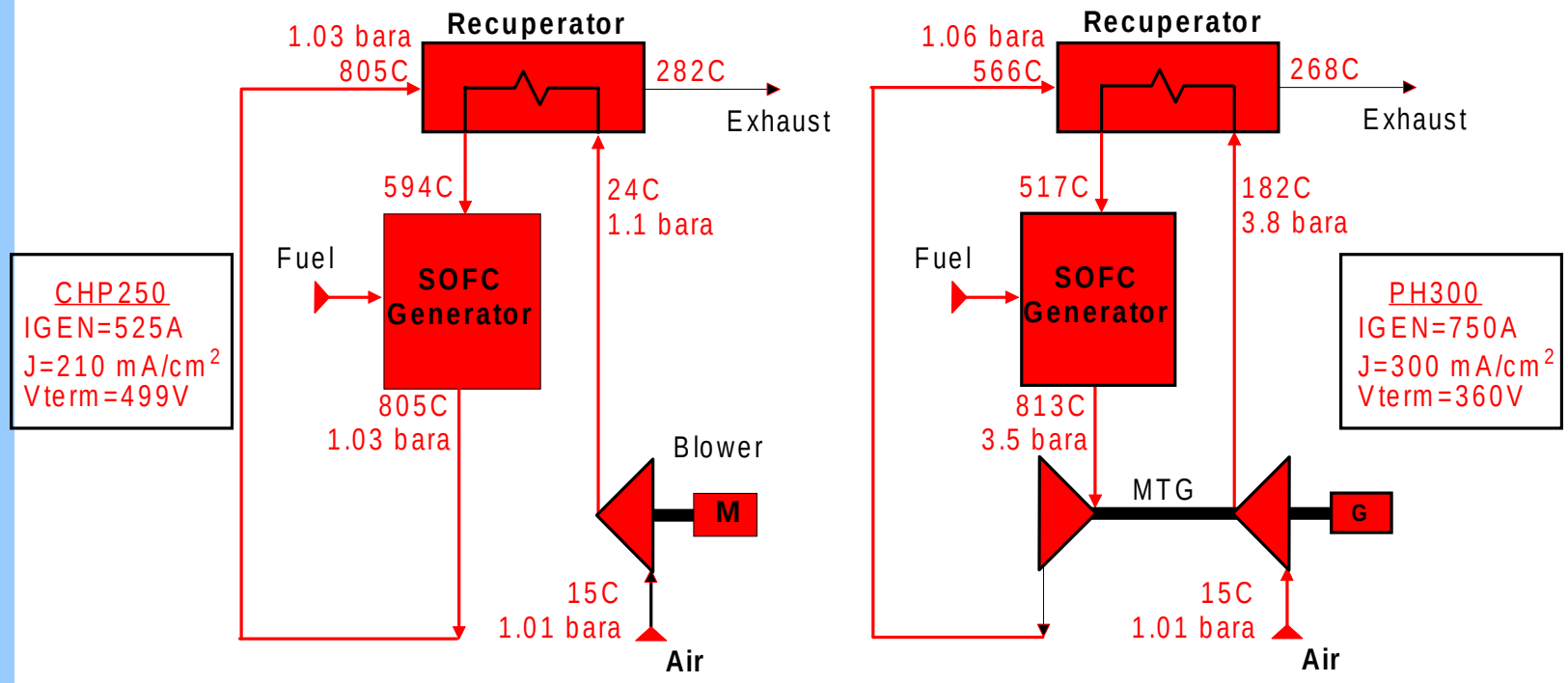
Typical Expected Conditions in the Cycle



Atmospheric Pressure
(CHP100, CHP250)

Pressurized Hybrid
(PH200, PH300, PH550)

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PH200 Proof-of-Concept System

- Built for Southern California Edison (SCE).
- Other participants:
  - US DOE
  - EPRI
  - California Energy Commission
  - South Coast Air Quality District
  - University of California at Irvine [UCI].
- IRES PowerWorks 75 MTG
- Located at and operated by UCI NFCRC
- SCE owns all project data; data are included in this presentation with SCE permission.

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- Power Module
  - PSOFC
  - MTG
  - Fuel Supply
  - Steam Supply
  - Electricals
- Off Skid
  - NG Compressor
  - Desulfurizer
  - Dissipator
- Dimensions
  - L = 7.2 m
  - W = 3.8 m
  - H = 3.7 m
- AES SOFCs
  - 1152

PH200 Proof-of-Concept System

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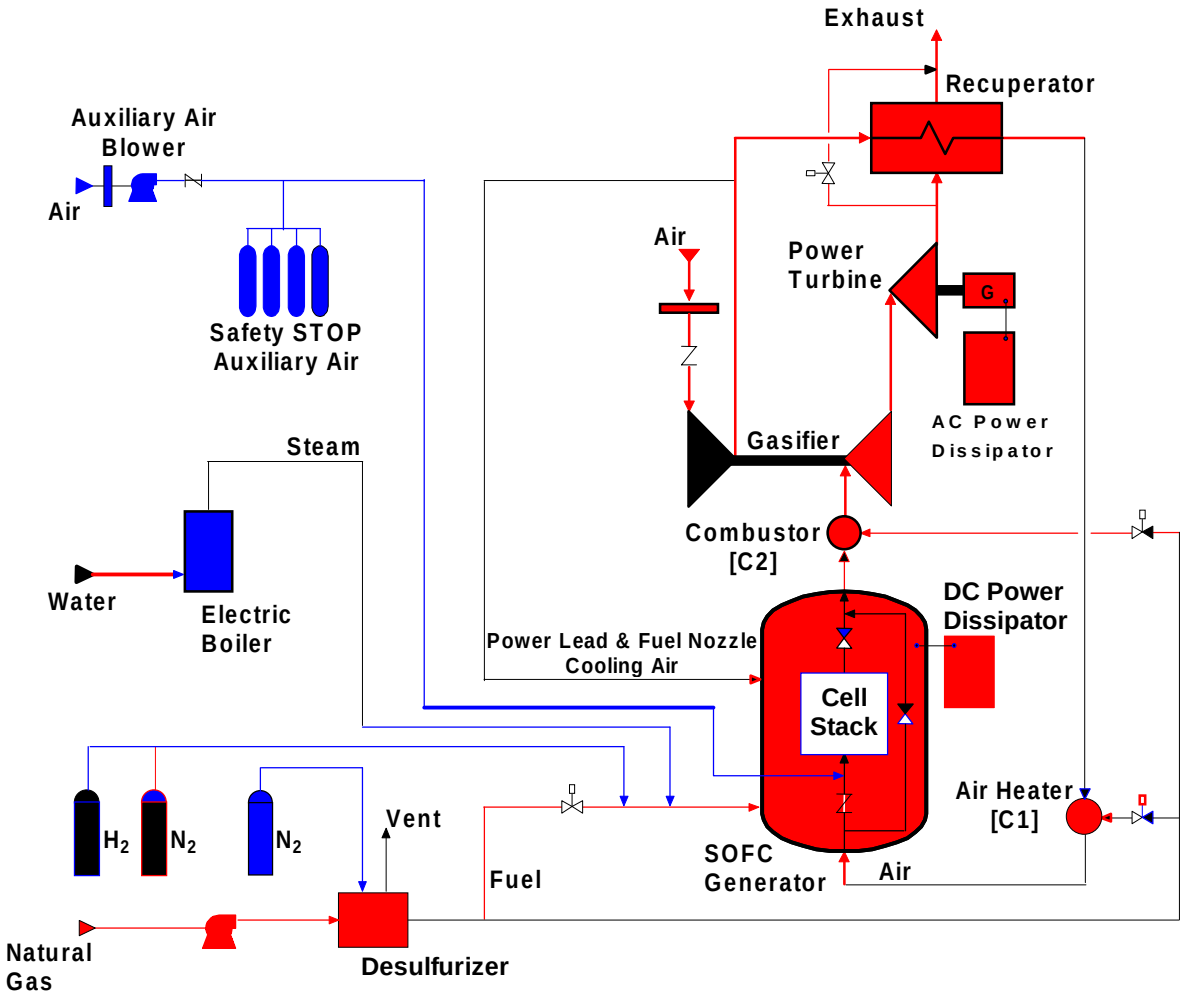
PH200 System Simplified Cycle Diagram



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- **FAT**
  - ➢ok
- **SAT1**
  - ➢Stack Error
  - ➢Power Lead
- **SAT2**
  - ➢Failed Cell
- **SAT3**
  - ➢MTG
  - ➢Problem
- **SAT4**
  - ➢?
- **FUTURE**
  - ➢?$$$?

PH200 System Operational Summary

Period of Operation	Date	Operating Hours [RUN]	SOFC DC Power Generated MWh	Total System AC Power* Generated MWh
FAT	25-Mar-2000 to 05-Apr-2000	110	16.1	17.4
SAT-1	03-Jun-2000 to 11-Jun-2000	154	23.8	25.5
SAT-2	08-Jan-2001 to 12-Feb-2001	514	84.1	88.2
SAT-3	08-Nov- 2001	0	0	0
SAT-4	31_Jan_2002 to 7_Apr_2002	1322	292.2	303.5

*Total system AC power [kW] = 0.94 * SOFC DC Power [kW] + MTG AC Power [kW] – 2.0 kW

Note: PH200 project data are owned by the Southern California Edison Company and are presented in this report with SCE permission.

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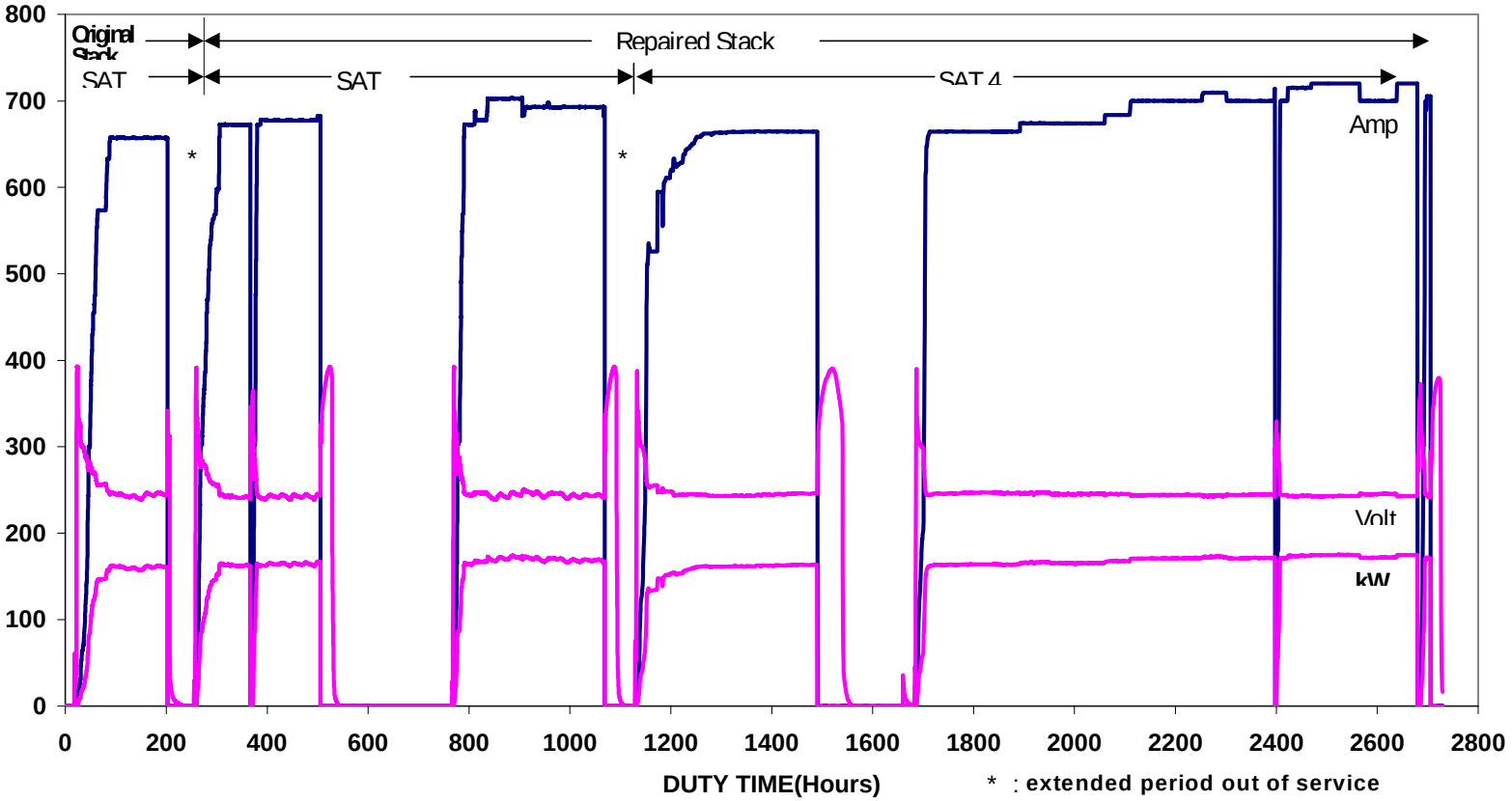
PH200 Operating History



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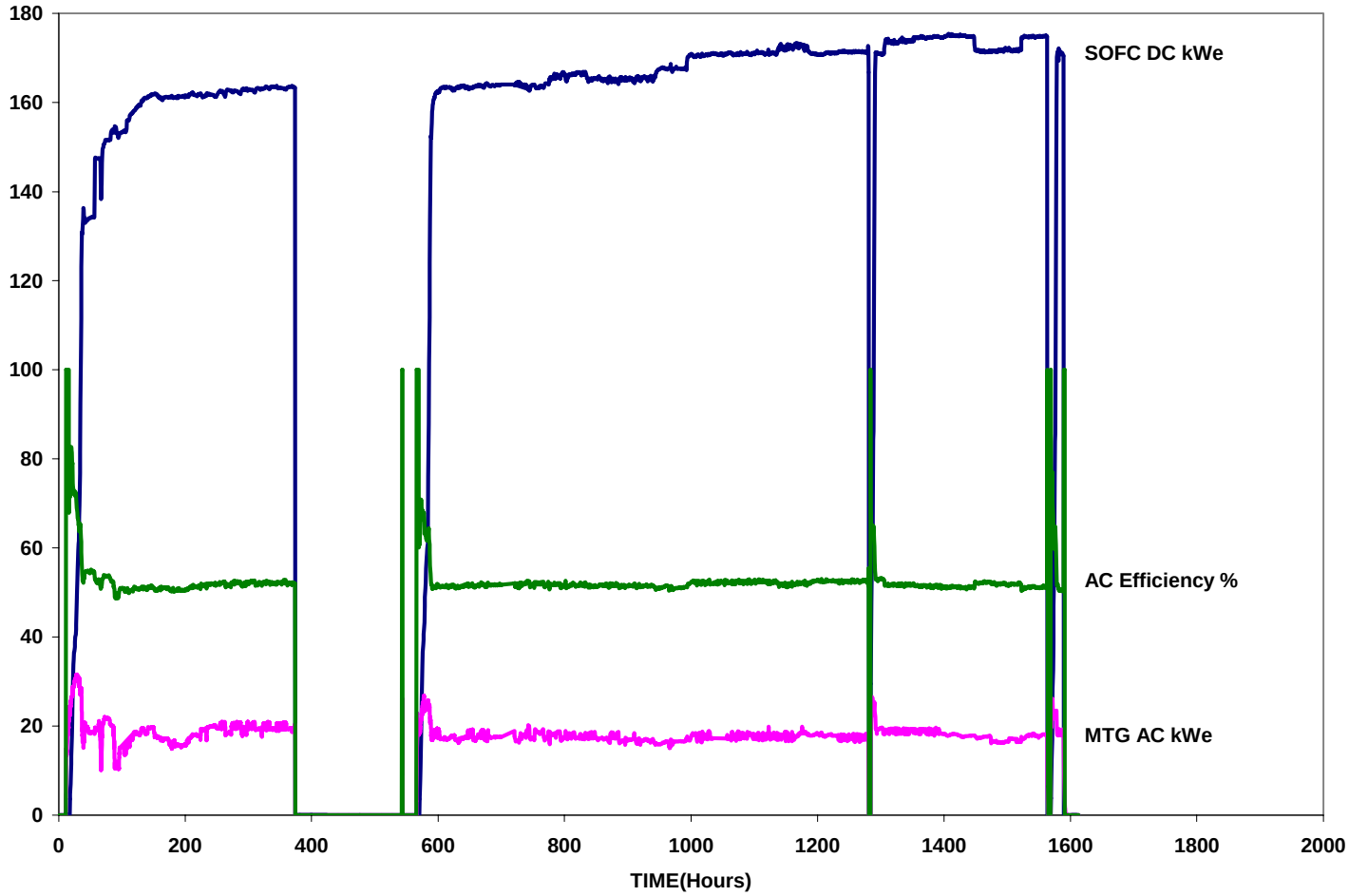
PH200 SAT-4 Operating History



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PH200 Proof-of-Concept Demonstration Accomplishments

- Un-manned operation
- World's first hybrid system
- Natural gas fueled
- In-stack reformation
- No external process water supply for SOFC generator operation
- Successful factory test
- Successful site start-up
- 182 kWe (ac basis)
- 53% electrical generation efficiency (ac basis)
- World's highest capacity SOFC power system
- 2000 hours of system operation

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PH300 Systems

- Contract was signed with RWE (as the leader of a European Consortium) in March 2000.
- PH300 system will be installed at the RWE Fuel Cell Pavilion in Essen, Germany; startup planned for mid-2002.
- Contract signed with Edison S.p.A (Italy) in July 2000.
- PH300 system will be installed in the Sinetta Marengo, Province of Alessandria in the Piedmont region, startup planned for early 2003.
- European MTG manufacturer [nominally 100 kWe]

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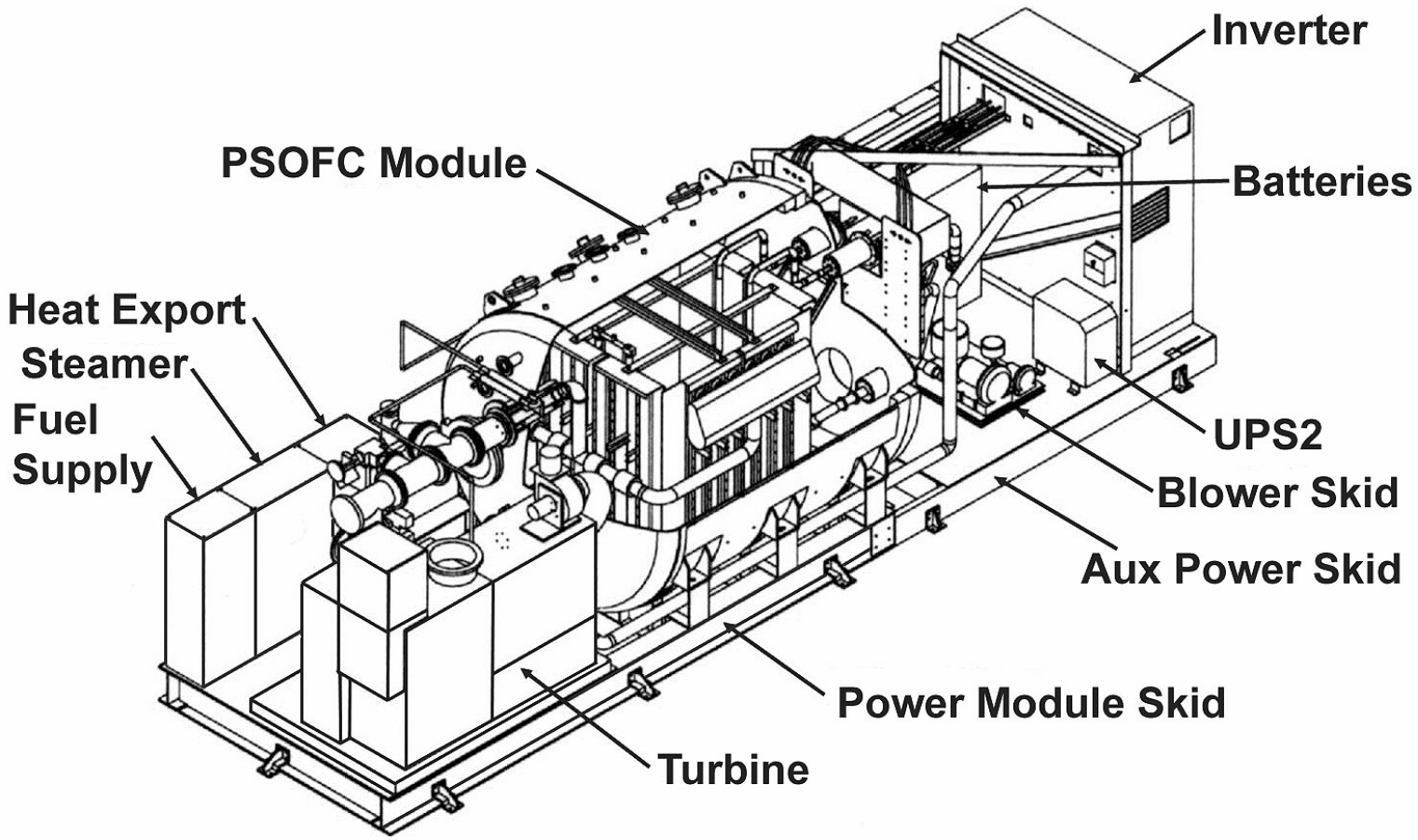
- Power Island
  - ➢Power Module
  - ➢Auxiliary Skid
- Power Module
  - ➢PSOFC
  - ➢MTG
  - ➢Heat Export
  - ➢Fuel Supply
  - ➢Steam Supply
- Auxiliary Skid
  - ➢PCS
  - ➢Electricals
  - ➢UPS
- Dimensions
  - ➢L = 12.8 m
  - ➢W = 3.6 m
  - ➢H = 3.7 m
- AES SOFCs
  - ➢1704
- Off Skid
  - ➢NG Compressor
  - ➢Desulfurizer

PH300 System Power Island



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PH300 SOFC Stack

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PH300 Pressure Vessel

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PH300 – MTG with Mini Pressure Vessel at FAT

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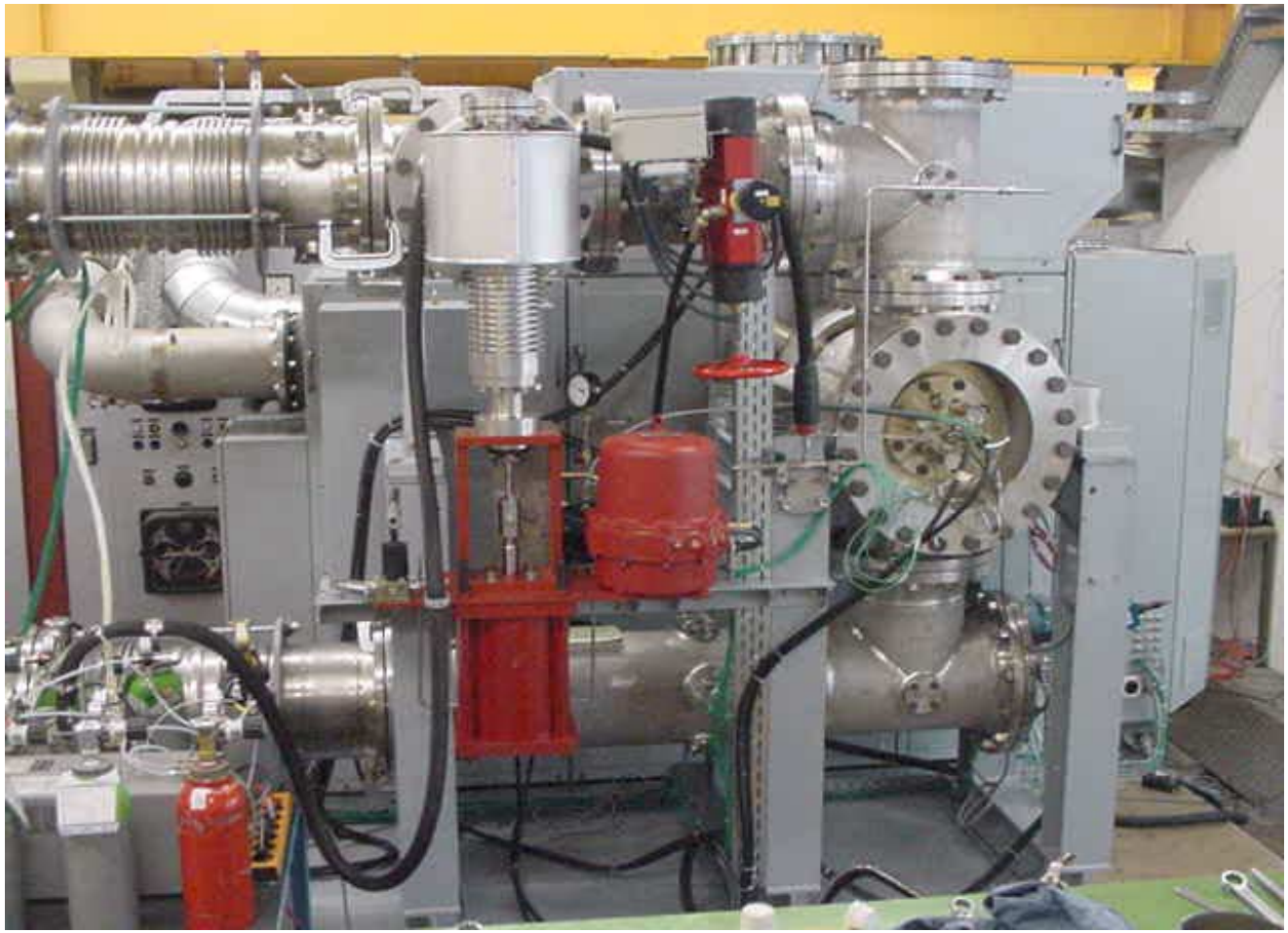
PH300 - MTG at Factory Acceptance Test



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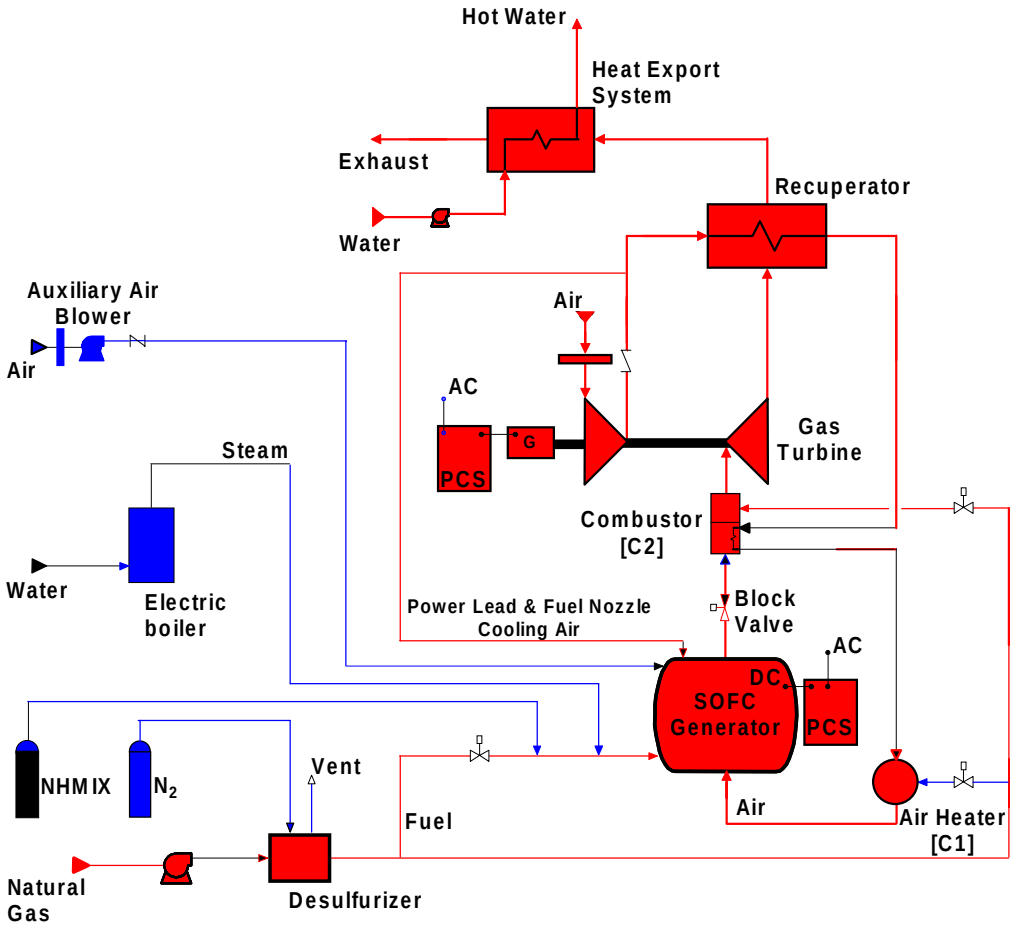
PH300 System Simplified Cycle Diagram



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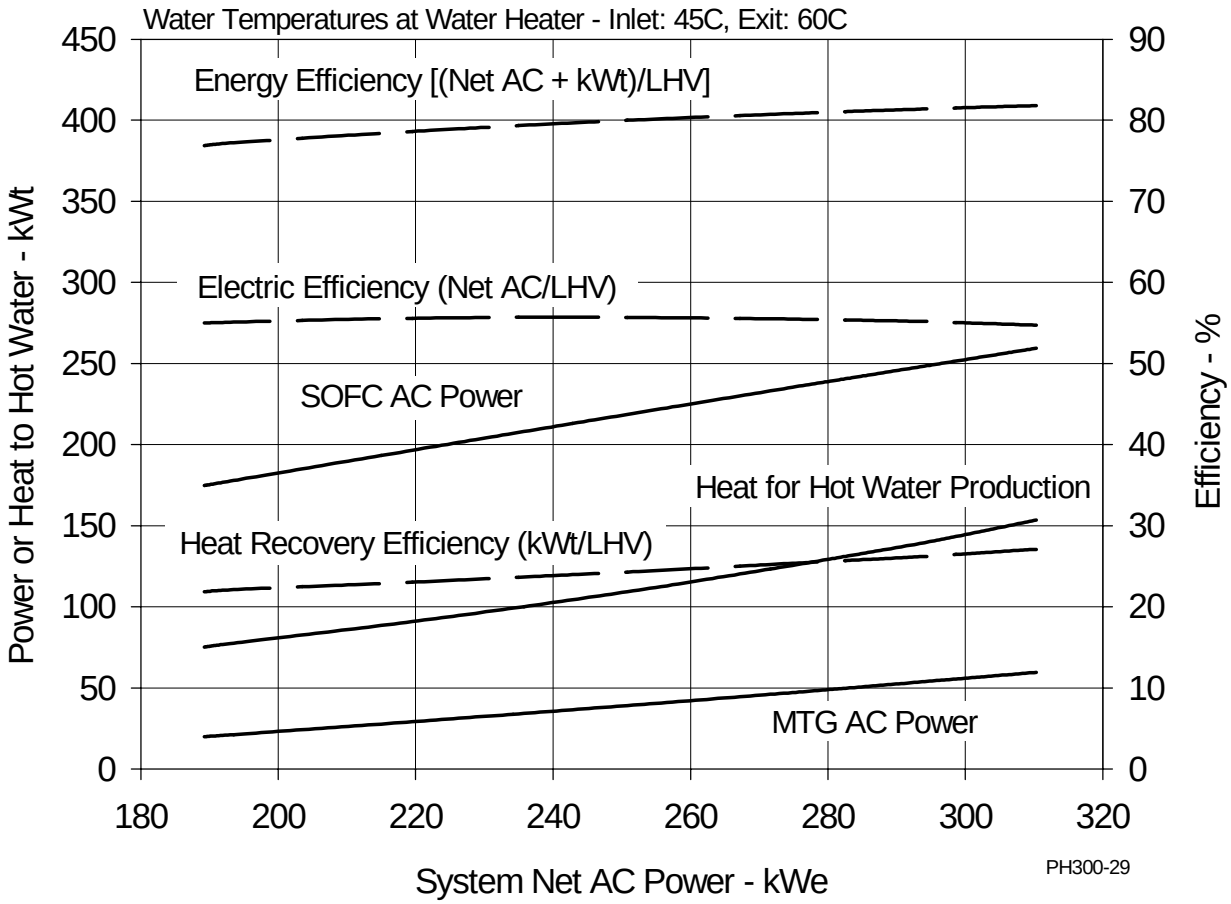
PH300 Estimated Performance vs Power

- **@ Max Power**
  - 302 kWe ac net
  - 55% efficiency
- **SOFC**
  - 750 Amps
  - 360 Volts
- **MTG**
  - PR=3.8
  - air = .649 kg/s
  - 57 kWe net
- **Hot Water**
  - Tout = 65°C
  - 146 kWt
- **Fuel Eff**
  - 81.6%



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PH550 System Planned

- MWe-class PSOFC/MTG system demonstration projects have been suspended - Power module size and weight presents formidable shipping problems and a suitable MTG is not available.
- Planned commercial PSOFC/MTG hybrid will be PH550.
- PH300 demonstrations are Proof-of-Concept experiments.
- PH550 product definition studies have been initiated.
- PH550 system prototype demonstration anticipated in late 2004 or early 2005, BUT suitable MTG needed.

Tubular SOFC Hybrids

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- Power Island
  - Power Module
  - Auxiliaries
- Power Module
  - PSOFC
  - MTG
  - Heat Export
- Auxiliary Skid
  - Power Conditioner
  - Electricals
  - UPS
  - Fuel Supply
  - Steam Supply
- Dimensions
  - L = 14 m
  - W = 3.6 m
  - H = 3.7 m
- AES SOFCs
  - 3408
- Off Skid
  - NG Compressor
  - Desulfurizer

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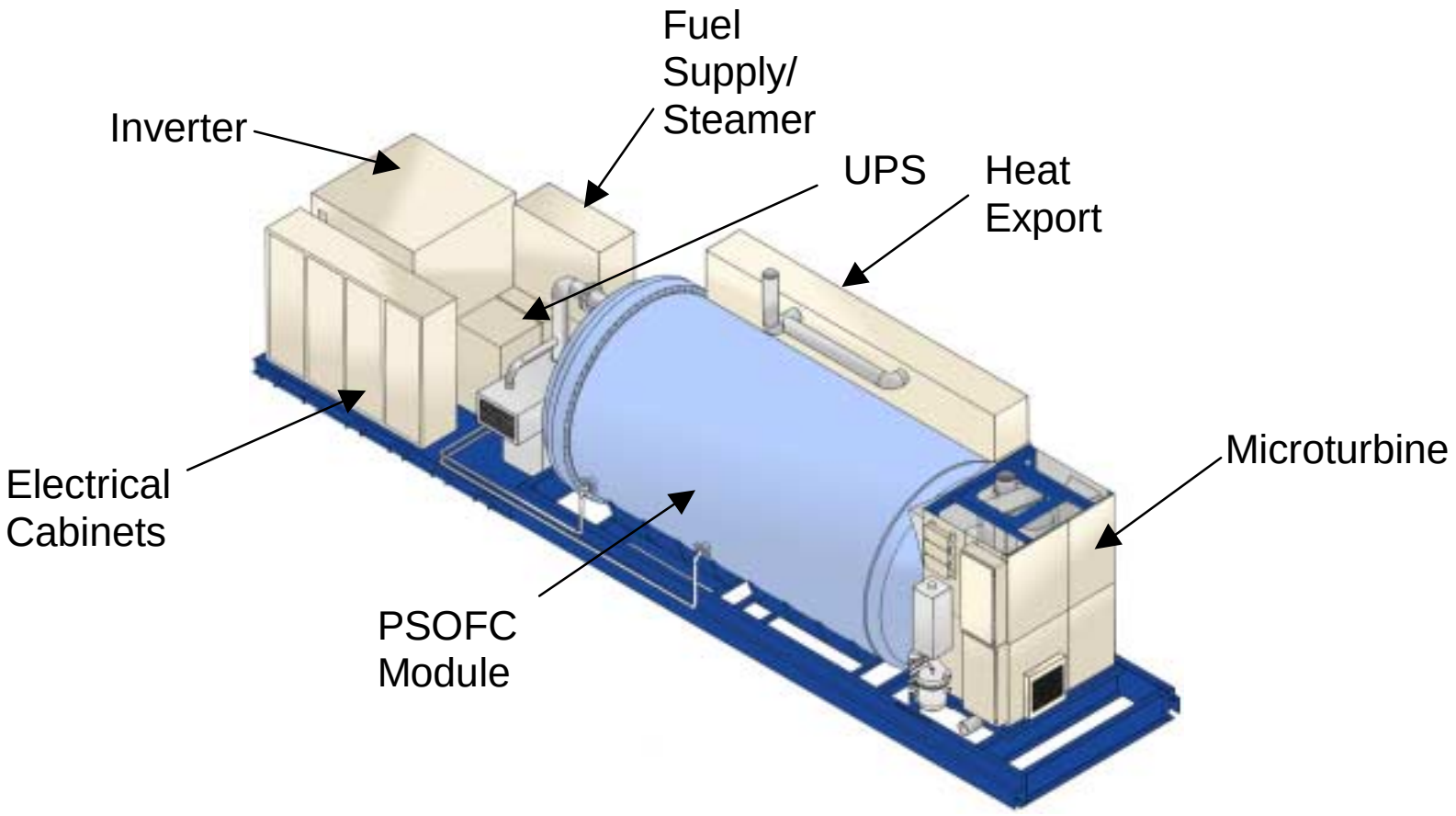
PH550 System Power Island



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PH550 Micro Turbine Generator

Nominal Performance Parameters

Air flow = 1.2 kg/s
PR = 3.6
TIT = 820 C
Power = 115 kWe

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Gas Turbine Features for PSOFC/MTG Application

- Turbine inlet temperature: 820°C < TIT < 950°C
- Compressor pressure ratio: 3:1 < Pr < 4:1
- High-effectiveness recuperator: ε >90%
- High GT combustor inlet air temperature (820°C to 870°C)
- High reliability – 8000 hours continuous operation.
- Wide combustor fuel flow modulation range – 5% to 110%
- Variable high-speed alternator, with associated electronics.
- Never-seize shaft design.
- Close SOFC/MTG package integration.
- Continuous operation during loss-of-grid events.
- Turbine generator motoring capability.

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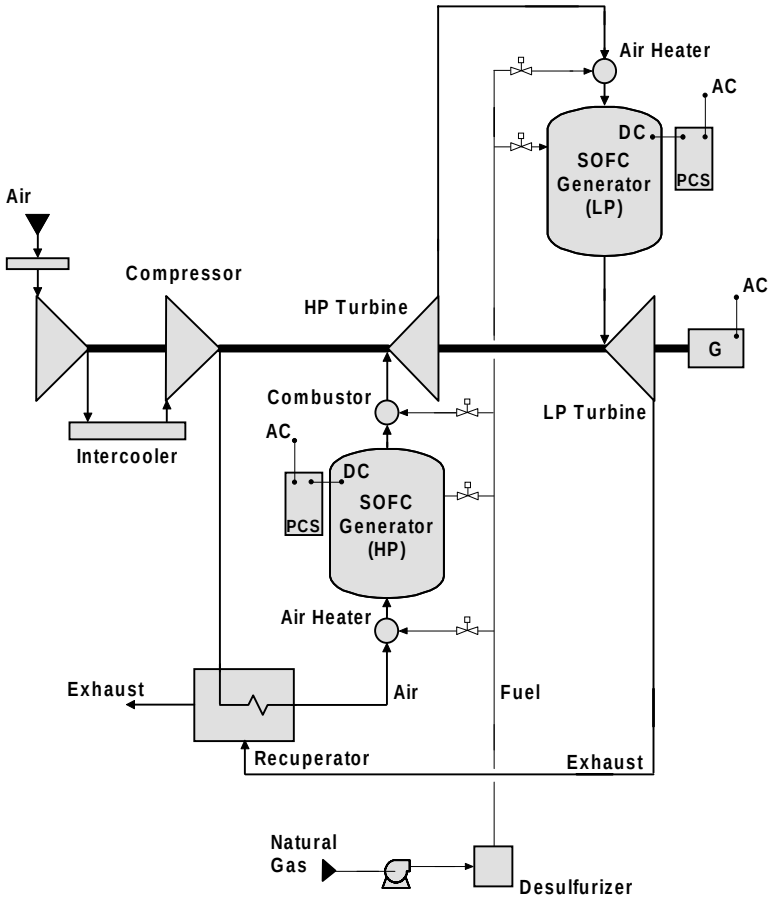
SOFC Future Potential
PSOFC/IRsofcR-GT Cycle ⇒ Higher Efficiency

- Intercooled
- Recuperated
- Reheated
- SOFC
  - ➢ High Pressure
  - ➢ Low Pressure
- Max Temp
  - ➢ 870°C
- PR = 7.1
- Efficiency
  - ➢ 70%
- $\frac{\text{SOFC kWe}}{\text{GT kWe}} = 4$



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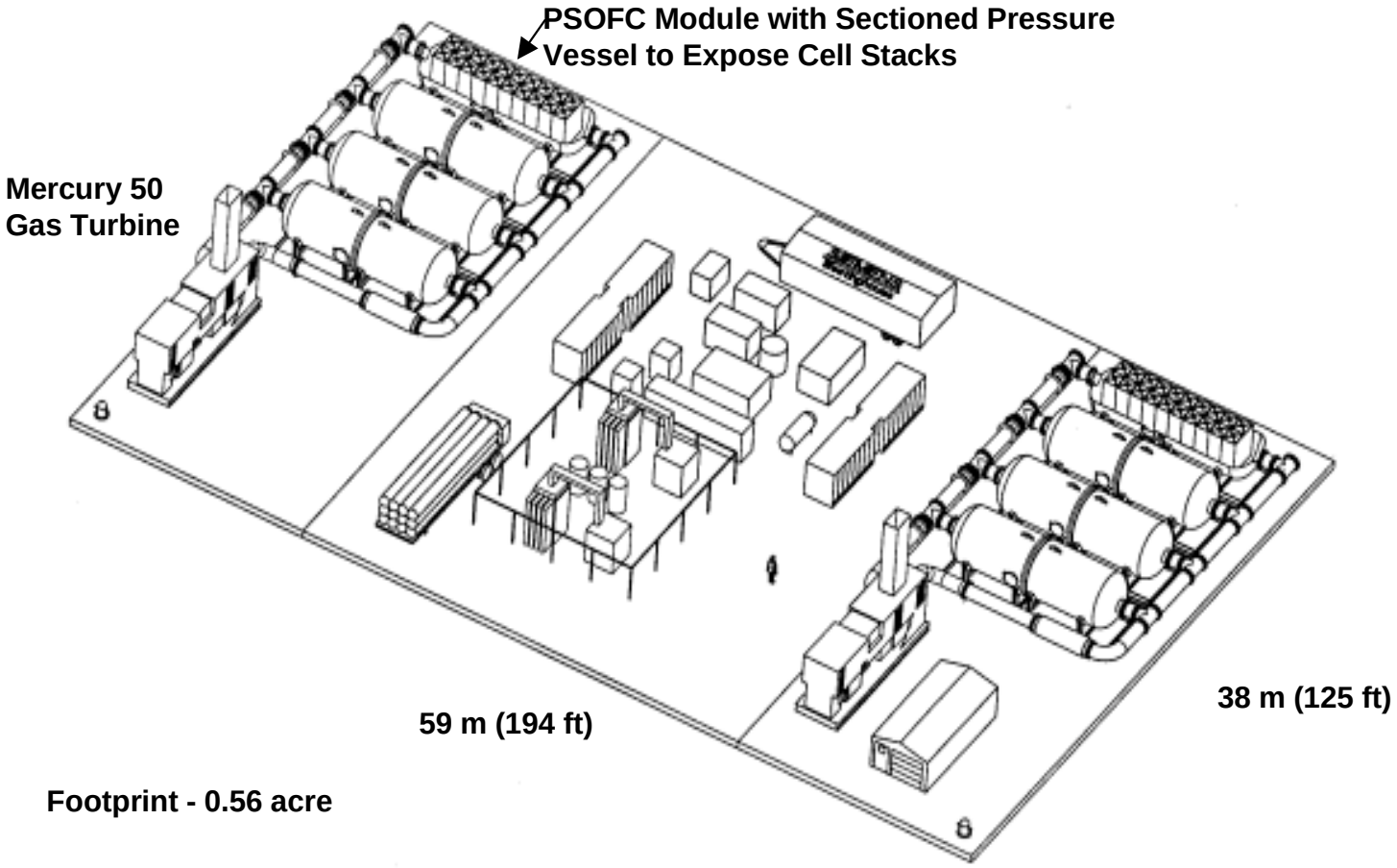
- Simple Cycle
- Fired ATS-GT
- TIT = 1160°C
- Mercury 50
- 12.3 MWe Power Block
- Efficiency 60%
- Less $/kWe
- $\frac{\text{SOFC kWe}}{\text{GT kWe}} = 1.6$

SOFC Future Potential
PSOFC/ATS-GT @ 25 MWe



Footprint - 0.56 acre

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Summary of Tubular SOFC Hybrid Program Status

- The CHP250----Product in 2003/2004
- The PH200-----Proof-of-Concept, 1st iteration
  - The first PSOFC/GT hybrid
  - 2000 power generation hours
  - Indicated system efficiency--- 53%
  - Two shaft microturbine generator, oversized
- The PH300-----Proof-of-Concept, 2nd iteration
  - Startup in 2002
  - Single shaft microturbine generator
  - Expected efficiency > 55%
- The PH550-----Product in 2005 ??…..Needs an MTG
- The PH @ Multi MWe-----Product in 2007 ??……Needs a GT
- The advanced cycles-----ATS-GT or IRR cycle…Needs a DOE funded development program for higher pressure SOFC stack and the GT.

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Conclusions

a) PH200 works, the first proof-of-concept.

b) PH300 will be in the field in 2002, the second proof-of-concept.

c) Simple PH cycle efficiency horizon is 60%.

d) A suitable MTG for PH550 and higher capacity units awaits development.

e) The GT for the PH is non exotic in material or features.

f) The GT for the PH requires customization for cycle integration.

g) SOFC PH with ATS-GT yields 60% efficiency at lesser cost (fewer fuel cells), BUT needs higher pressure SOFC stack development & ATS-GT.

h) Integration with the Solar Mercury 50 ATS yields 12 MWe SOFC PH, technically feasible in 5 years if development is funded.

i) IRsofcR PH cycle efficiency horizon is 70% at multi MWe capacity, BUT requires reheat GT and higher pressure SOFC stack development.

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Emissions Comparison

Power System Type	Efficiency %	CO_2 kg/MWh	NOx g/MWh
CHP250 – Nominal Power	46	430	20 (1 ppm)
PH300 – Nominal Power	55	370	13 (1 ppm)
12 MWe PSOFC/ATS-GT Power System	60	340	40 (5 ppm)
20 MWe IRSOFCR Power System	67	300	6 (1 ppm)
MicroTurbine (< 100 kWe)	25	850	480 (9 ppm)
Conventional GT/ST Combined Cycle *	57	370	270 (25 ppm)
Advanced (ATS) GT/ST Combined Cycle *	60	350	90 (9 ppm)
Steam Turbine Power Plant (Coal) *	35	900	2300 (300 ppm)

* Large Plants, 100s MWe